Triakis Corporation

System Requirements Specification

For the

Shuttle Remote Manipulator System

A NASA CI03
SARP Initiative 583
IVV-70 Project

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1. Introduction

This specification is being developed to support a research project funded by the NASA Software Assurance Research Program (SARP) during the fiscal year 2003 Center Initiatives (CI03) effort. A simulation of the Shuttle Remote Manipulator System (SRMS) will be created from the requirements specified herein and used as a vehicle for exploring the concepts described in section 2 of Triakis proposal number TC_G020614.

The format and content of this specification is intended to follow the guidelines established in IEEE-1233-1998. However, since the virtual SRMS will be modeled on the existing design employed in the Space Shuttle program, many of the system requirements listed herein are, of necessity, implementation specific. As our project effort progresses, this specification will be updated to reflect changes to the scope and fidelity of system requirements due to an improved understanding of the extent that our virtual SRMS must be developed to support our research goals.

In the normal course of events, the system requirements specification (SyRS) addresses all system-level aspects of the project being developed while avoiding implementation-specific requirements. The SyRS then becomes the basis for developing both the physical system, and the virtual system (i.e. the system simulator).

When used solely for the purposes of Independent Verification & Validation (IV&V), the virtual system must be created to mirror the physical system as described in the system design document (SyDD). A suite of tests is written to verify and validate the system design in the virtual environment, against the requirements specified in the SyRS.

When used directly in the project development cycle, the virtual system is developed as a tool for designing and validating the system architecture. The developed and tested virtual system with its collection of individual executable specifications, referred to as the virtual system integration laboratory (VSIL), forms the basis for the system design document. The SyRS, SyDD, VSIL, and supporting suite of tests are delivered to the component development teams (both in-house and subcontracted) to be used as the unambiguous specification standard to which equipment will be developed & tested. The SyRS, SyDD, and VSIL (without the supporting suite of tests) are also delivered to the IV&V group for use in their independent analysis and testing efforts.

In both cases, a high-fidelity hardware simulation of each embedded computer-controlled design will be created. The simulated hardware, together with the controlling software designed for the real-world counterpart is referred to as the detailed executable (DE). When the DE is substituted for its ES precursor in the VSIL, the system designers and the IV&V team alike may test the integrity of the executable SW the using the same tests developed for system-level V&V. Each part within the VSIL may be designed to incorporate built-in failure modes that can be invoked under test control to evaluate system and SW behavior in response to component degradation or loss.

The simulator developed for this project will be used to evaluate the extent to which the Triakis concept of Executable Specifications (ES') achieves unambiguous communication of system requirements thereby reducing errors induced by interpretation of ambiguous specifications. It will also be used to evaluate the potential that substituting a detailed executable (DE) hardware simulation running actual embedded software, in place of the ES, has for reducing costs and maintaining test consistency through reuse of unmodified system level tests.

Further, new methods of gathering software metrics through use of the simulator will be sought, explored, and evaluated. The use of a virtual system simulator developed for this project will be used to evaluate other potential benefits that its virtual system integration laboratory (VSIL) environment offers in support of general testability, independent validation & verification (IV&V), reliability, and safety.

1.1 System purpose

The system specified herein is intended to represent the SRMS in a general sense only. The system requirements laid out in this document will form the basis for creating a virtual system simulator that will be used as a vehicle to facilitate the research goals stated in Triakis proposal number TC_G020614. As such, system components and functions of the real-world SRMS that are not required to support our research goals have been omitted.

While the purpose of the actual SRMS is to facilitate the deployment and retrieval of shuttle payloads as well as extra-vehicular activity missions, the derivative SRMS will not incorporate functioning end-effectors required for these purposes. The specified SRMS will demonstrate the control and movement capability of the RMA along with integral shuttle orbiter-protective safeguards.

1.2 System scope

This document specifies a subset of the system characteristics of the existing NASA space shuttle RMS. Adaptations to the functionality of the actual SRMS will be incorporated to the extent required for the stated research purposes and demonstration of the research results.

1.3 Definitions, acronyms, and abbreviations

CCTV	Closed-Circuit Television
CI03	Center Initiative for fiscal year 2003
C/W	Caution/Warning
DE	Detailed Executable
ES	Executable Specification
EVA	Extra Vehicular Activity
IV&V	Independent Verification and Validation
N/A	Not Applicable
NASA	National Aeronautics & Space Administration
OSMA	Office of Safety and Mission Assurance
PDRS	Payload Deployment and Retrieval System
RHC	Rotational Hand Controller
RMA	Remote Manipulator Arm
RMS	Remote Manipulator System
RMSCC	RMS Control Computer
SARP	Software Assurance Research Program
SRMS	Shuttle Remote Manipulator System
SyDD	System Design Document
SyRS	System Requirements Specification
THC	Translational Hand Controller
VSIL	Virtual System Integration Laboratory

1.4 References

http://spaceflight.nasa.gov/shuttle/reference/index.html	NASA Shuttle Reference web site
http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/sts-deploy	NASA PDRS web page
IEEE-1233-1998	IEEE Guide for Developing System Requirements Specifications
ISBN 0-345-34181-3	Joels, Kennedy & Larkin; Ballantine books, 1988: The Space Shuttle Operator's Manual (Revised Edition)
TC_G020614	Triakis proposal to NASA for the SARP (Solicitation No: NRA SARP 0201) 14 June 2002

1.5 System overview

The following excerpt from the NASA PDRS web page provides an excellent overview of the SRMS:

> *The payload deployment and retrieval system (PDRS) includes the electromechanical arm that maneuvers a payload from the payload bay of the space shuttle orbiter to its deployment position and then releases it. It can*

also grapple a free-flying payload, maneuver it to the payload bay of the orbiter and berth it in the orbiter. This arm is referred to as the remote manipulator system (RMS).

The shuttle RMS is installed in the payload bay of the orbiter for those missions requiring it. Some payloads carried aboard the orbiter for deployment do not require the RMS.

The RMS is capable of deploying or retrieving payloads weighing up to 65,000 pounds. The RMS can also retrieve, repair and deploy satellites; provide a mobile extension ladder for extravehicular activity crew members for work stations or foot restraints; and be used as an inspection aid to allow the flight crew members to view the orbiter's or payload's surfaces through a television camera on the RMS.

2. General system description

The general system description provided below is an excerpt from the NASA PDRS web page. This description is intended to give a general picture of the system functionality upon which the system specified herein is derived.

The basic RMS configuration consists of a manipulator arm; an RMS display and control panel, including rotational and translational hand controllers at the orbiter aft flight deck flight crew station; and a manipulator controller interface unit that interfaces with the orbiter computer. Normally, only one RMS is installed during a shuttle mission, on the left longeron of the orbiter payload bay.

The RMS arm is 50 feet 3 inches long, 15 inches in diameter, and has six degrees of freedom. The six joints of the RMS correspond roughly to the joints of the human arm with shoulder yaw and pitch joints; an elbow pitch joint; and wrist pitch, yaw and roll joints. The end effector is the unit at the end of the wrist that actually grabs, or grapples, the payload.

The RMS can only be operated in a zero gravity environment, since the arm dc motors are unable to move the arm's weight under the influence of Earth's gravity. Each of the six joints has an extensive range of motion, allowing the arm to reach across the payload bay, over the crew compartment or to areas on the undersurface of the orbiter. Arm joint travel limits are annunciated to the flight crew arm operator before the actual mechanical hard stop for a joint is reached.

One flight-crew member operates the RMS from the aft flight deck control station, and a second flight-crew member usually assists with television camera operations. This allows the RMS operator to view RMS operations through the aft flight deck payload and overhead windows and through the closed-circuit television monitors at the aft flight deck station.

The orbiter's CCTV aids the flight crew in monitoring PDRS operations. The arm has provisions on the wrist joint for a CCTV camera that can be zoomed, a viewing light on the wrist joint and a CCTV with pan and tilt capability on the elbow of the arm. In addition, four CCTV cameras in the payload bay can be panned, tilted and zoomed. Keel cameras may be provided, depending on the mission payload. The two CCTV monitors at the aft flight deck station can each display any two of the CCTV camera views simultaneously with split screen capability. This shows two views on the same monitor, which allows crew members to work with four different views at once. Crewmembers can also view payload operations through the aft flight station overhead and aft (payload) viewing windows.

The arm has a number of operating modes. Some of these modes are computer-assisted, moving the joints simultaneously as required to put the end point (the point of resolution, such as the tip of the end effector) in the desired location. Other modes move one joint at a time; e.g., single mode uses software assistance and direct and backup hard-wired command paths that bypass the computers.

Four RMS manually augmented modes are used to grapple a payload and maneuver it into or out of the orbiter payload retention fittings. The four manually augmented modes require the RMS operator to use the RMS translational hand controller (THC) and rotational hand controller (RHC) with the computer to augment operations.

The THC and RHC located at the aft flight deck station are used exclusively for RMS operations. The THC is located between the two aft viewing windows. The RHC is located on the left side of the aft flight station below *the CCTV monitors. The THC and RHC have only one output channel per axis. Both RMS hand controllers are proportional, which means that the command supplied is linearly proportional to the deflection of the controller.*

There are two types of automatic modes that can be used to position the RMS arm: operator-commanded and preprogrammed.

The operator-commanded automatic mode moves the end effector from its present position and orientation to a new one defined by the operator via the keyboard and RMS CRT display. The arm moves in a straight line to the desired position and orientation and then enters the hold mode.

The preprogrammed auto sequences operate in a manner similar to the operator-commanded sequences. Instead of the RMS operator entering the data on the computer via the keyboard and CRT display, the RMS arm is maneuvered according to a command set programmed before the flight, called sequences. Each sequence is an ordered set of points to which the arm will move. Up to 200 points may be preprogrammed into as many as 20 sequences.

The standard end effector can be considered the hand of the RMS. It is a hollow can-like device attached to the wrist roll joint at the end of the arm. Payloads to be captured by the standard end effector must be equipped with a grapple fixture. To capture a payload, the flight crew operator aligns the end effector over the grapple fixture probe to capture it. The end effector snare consists of three cables that have one end attached to a fixed ring and one attached to a rotating ring.

Unless expressly indicated, subsequent references to all elements of the SRMS and surrounding systems within this document are to be construed as referring to system elements within the derived system and not the actual SRMS (in use on the NASA shuttle program) on which the derived system is based.

3. System performance characteristics

3.1 System context

The SRMS is intended be a self-contained system with few connections to the shuttle within which it will function. Figure 1 depicts the actual RMA (upon which this one is based) with major parts identified and its typical location within the shuttle orbiter. Neither the manipulator positioning mechanism nor a functioning end effector will be implemented in this SRMS.

R1: The SRMS shall be placed within the shuttle orbiter cargo bay attached to the portside cargo door support longeron as indicated in Figure 1.

R2: The SRMS shall draw power from the space shuttle 28VDC and 115VAC/400Hz power supplies as required to function as specified.

R3: The RMS control & display panel and the closed circuit television (CCTV) monitors that the crew employs in the operation of the SRMS shall be located on the orbiter flight deck at the aft crew station.

3.2 Major system components

R4: The SRMS shall comprise three principal elements:

a) A remote manipulator arm (RMA) (Figure 1),

b) A RMS control & display panel (Figure 2), and

c) A RMS control computer (RMSCC).

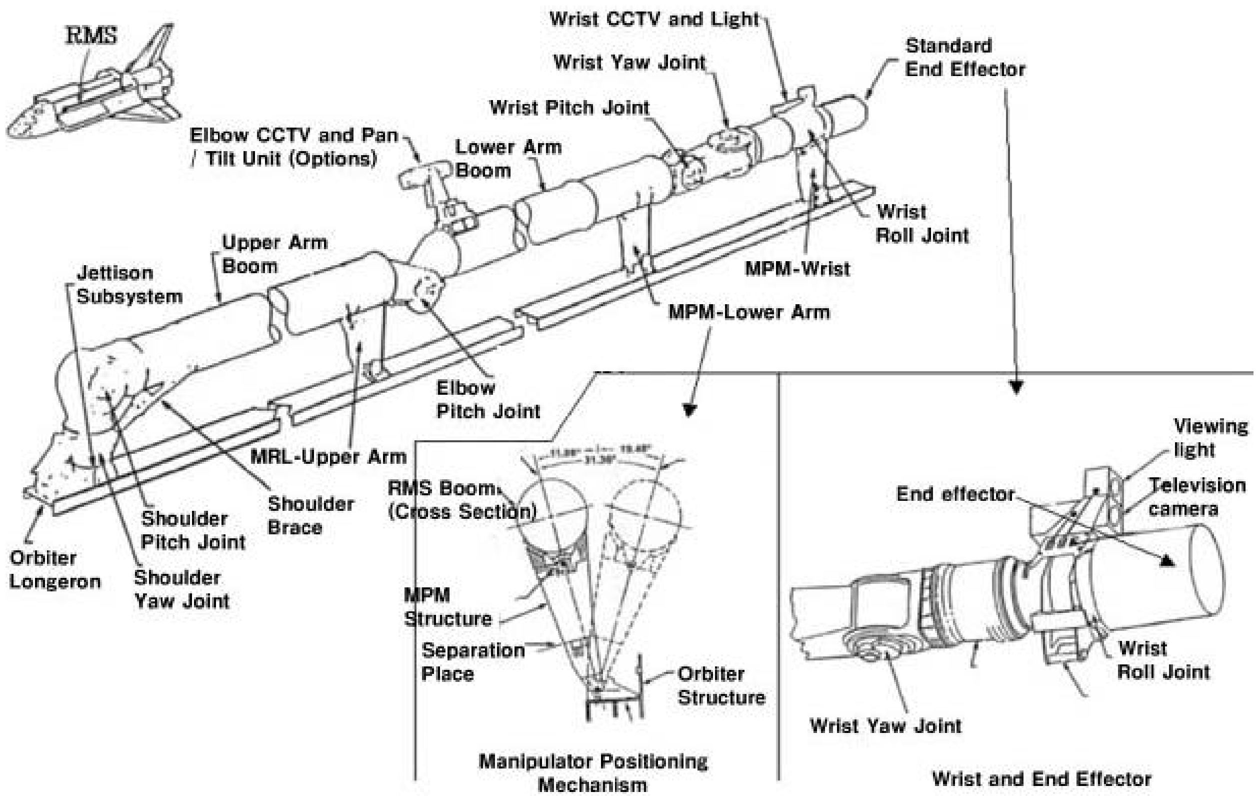


Figure 1: Remote Manipulator Arm

R5: Closed-circuit television (CCTV) monitors shall also be implemented as a means of visually monitoring RMA activity during operation.

R6: The RMSCC shall provide the main interface between the RMS control & display panel and the RMA itself.

3.3 System modes and states

Figure 2 is an illustration of the RMS control & display panel located in the real-world shuttle at the aft crew station shown in Figure 3 and Figure 4. Selection of the various operational modes and states is achieved through operator command via the RMS control & display panel. The SRMS will not implement all of the functions and modes incorporated in its real-world counterpart and therefore will not make use of some of the buttons, indicators, switches, and switch states shown on the panel in Figure 2.

R7: The SRMS shall support two manual operational control modes – single-joint control and angle-seek control.

R8: Single-joint manual control shall allow the operator to move the RMA one joint at a time.

R9: The operator shall be able to select any one of the RMA joints to increment/decrement the joint angle, and stop it on command.

R10: Angle-seek mode shall provide for computer-assisted manual RMA control.

R11: The computer control shall be optimized so that the joint travels in the direction of the shortest distance to the destination angle.

R12: The operator shall be able to read the current joint angle and graphically select a desired destination angle to which the joint shall automatically move and come to rest.

R13: The operator shall be able to stop individual joints from moving at any time.

R14: All joints shall immediately come to rest when the control mode is changed.

R15: Individual joints shall automatically hold their position after coming to rest.

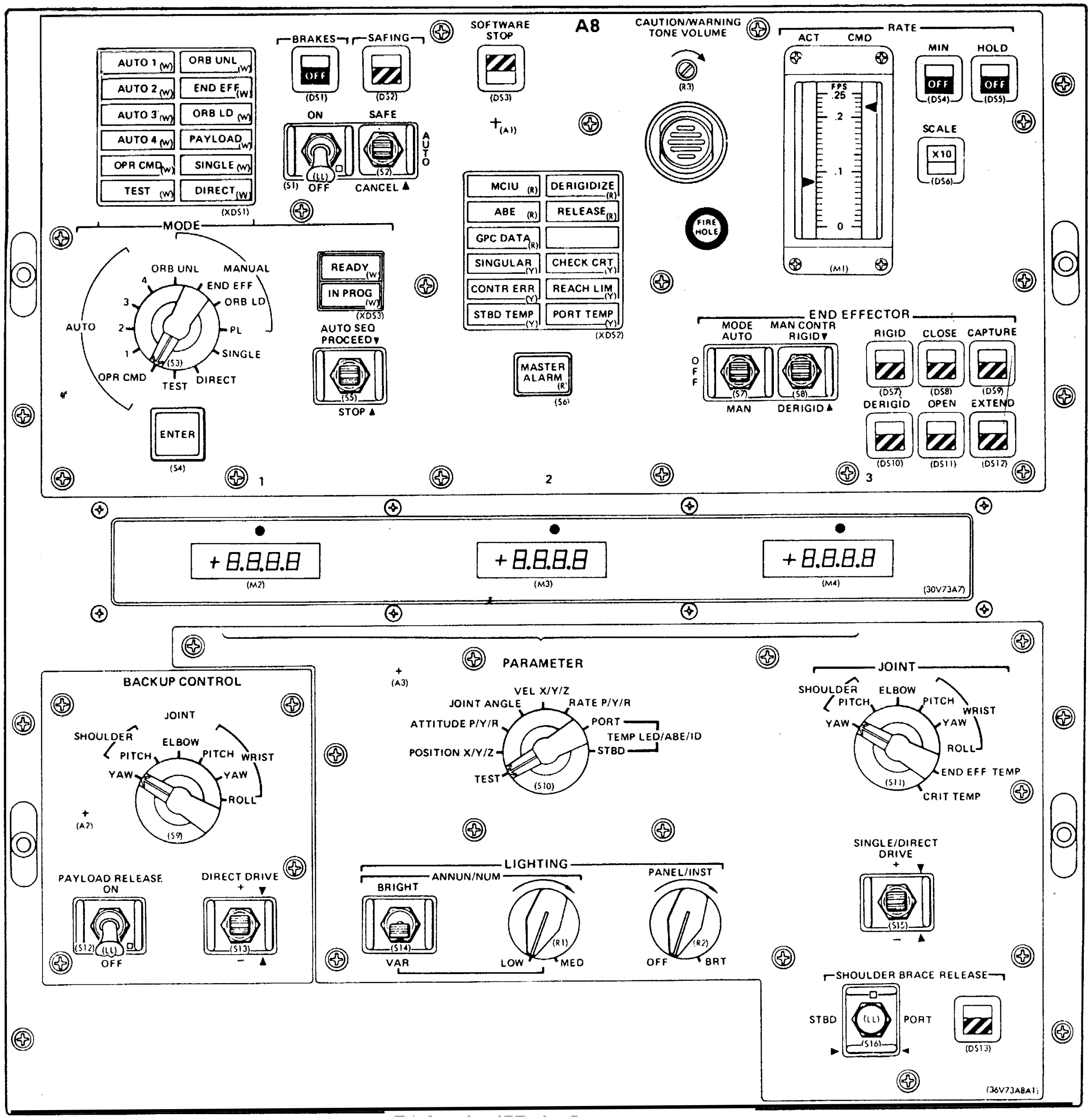


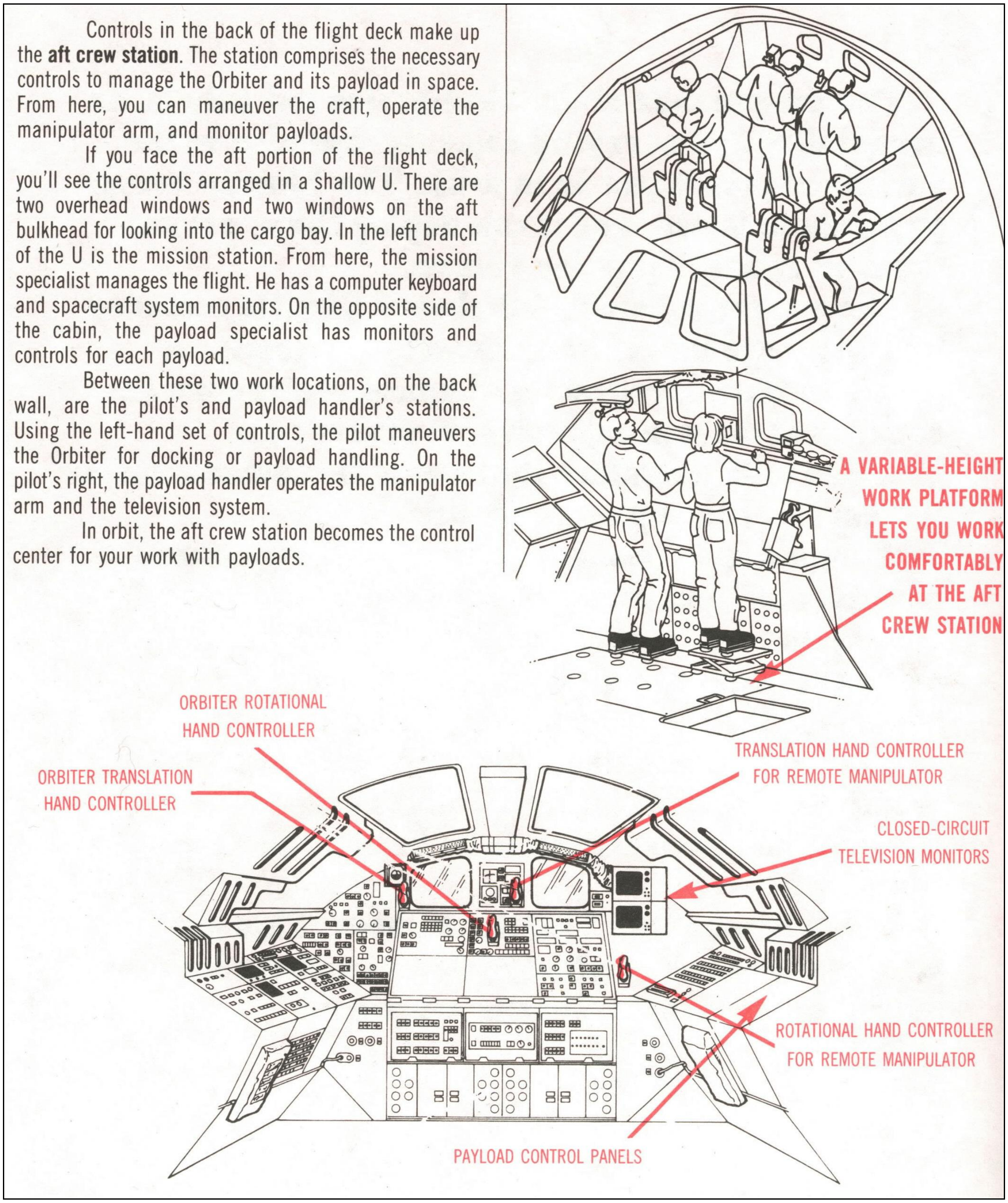
Figure 2: RMS Control & Display Panel (Courtesy of: *The Space Shuttle Operator's Manual*)

3.4 Major system capabilities

R16: The RMA shall be constructed with 6 degrees of freedom corresponding roughly to the joints of the human arm i.e.: shoulder yaw & pitch joints; elbow pitch joint; and wrist pitch, yaw, & roll joints.

R17: Normal braking shall be accomplished through deceleration of each joint motor.

R18: Each RMA joint shall hold the arm in position after it comes to rest.



Controls in the back of the flight deck make up the **aft crew station**. The station comprises the necessary controls to manage the Orbiter and its payload in space. From here, you can maneuver the craft, operate the manipulator arm, and monitor payloads.

If you face the aft portion of the flight deck, you'll see the controls arranged in a shallow U. There are two overhead windows and two windows on the aft bulkhead for looking into the cargo bay. In the left branch of the U is the mission station. From here, the mission specialist manages the flight. He has a computer keyboard and spacecraft system monitors. On the opposite side of the cabin, the payload specialist has monitors and controls for each payload.

Between these two work locations, on the back wall, are the pilot's and payload handler's stations. Using the left-hand set of controls, the pilot maneuvers the Orbiter for docking or payload handling. On the pilot's right, the payload handler operates the manipulator arm and the television system.

In orbit, the aft crew station becomes the control center for your work with payloads.

Figure 3: Shuttle orbiter aft flight deck crew station
(Courtesy of: *The Space Shuttle Operator's Manual*)

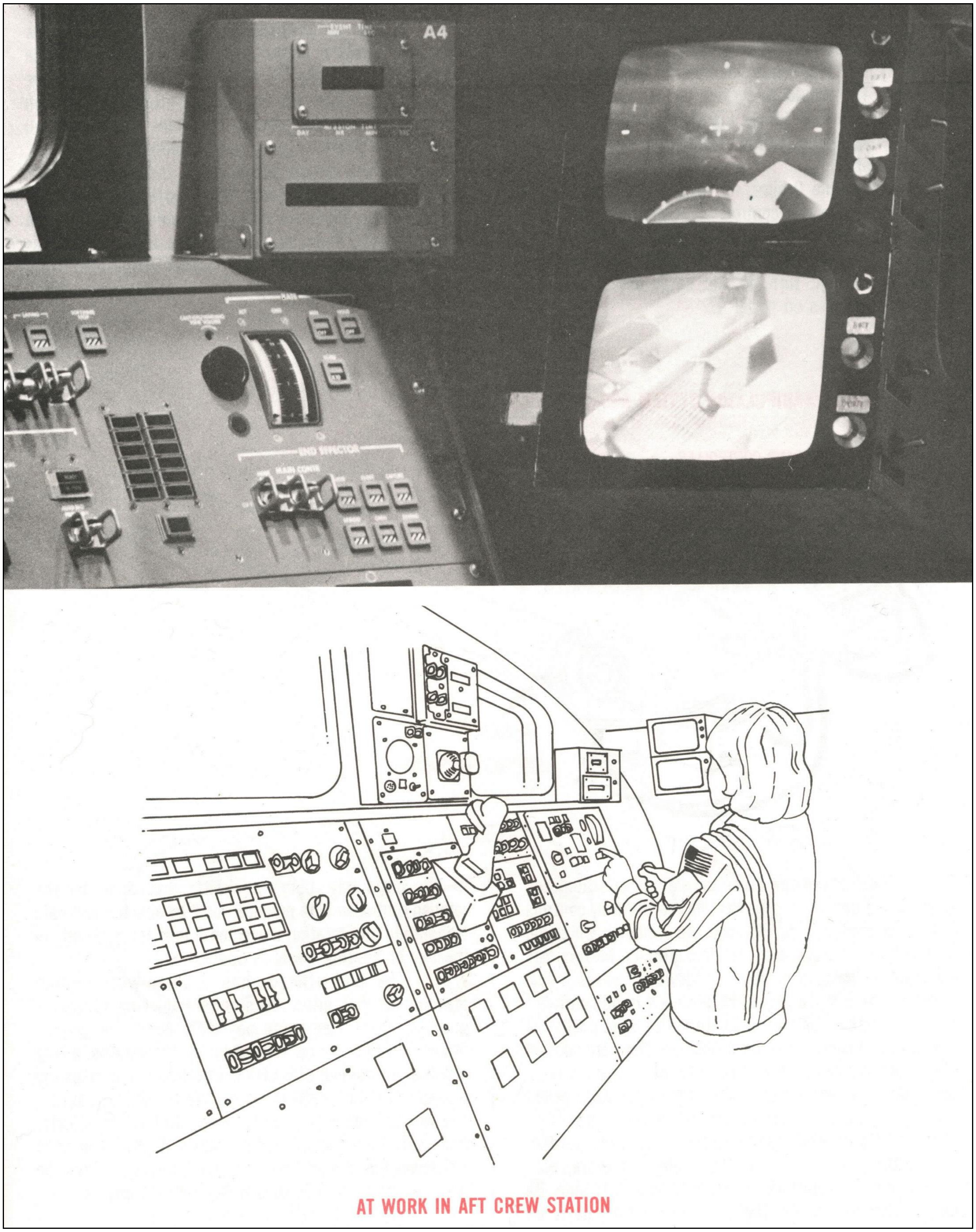


Figure 4: RMS installation in shuttle orbiter aft flight deck crew station
(Courtesy of: *The Space Shuttle Operator's Manual*)

R19: The RMA dimensions shall be approximately proportional to those of its real-world counterpart whose 13-inch diameter upper and fore arms have lengths of 17 and 20 feet respectively.

R20: The shuttle orbiter image used shall establish the scale size to which the RMA shall be rendered.

R21: The RMA upper and lower arm booms shall be instrumented with force sensors that can be read by the RMSCC to measure the torque that that the booms experience under dynamic loading.

R22: The RMA upper and lower arm booms and wrist joint shall each incorporate a CCTV camera with pan and tilt and zoom capability.

R23: The shuttle orbiter shall incorporate two CCTV cameras in the payload bay mounted to the forward and aft bulkheads that can be panned, tilted and zoomed.

R24: The two CCTV monitors at the RMS control & display panel shall each be capable of displaying any of the CCTV camera views.

3.5 Testability

R25: In order to exercise the system response to failures, the system shall be designed for easy fault injection to simulate known or theoretical failure modes of critical parts that can have a detrimental effect on safe operation of the RMA.

R26: A set of tests designed to verify SRMS conformance to the functional characteristics specified herein shall be written to exercise the virtual SRMS.

3.6 System constraints & safety considerations

Most constraints of the SRMS are imposed for safety related reasons. Given its movement capability, the RMA has the potential to collide with the shuttle orbiter as well as payload modules within the orbiter's cargo bay. Careful consideration must be given in all aspects of the SRMS design to prevent such collisions from occurring. However, since no real hardware will be built for this project, safety constraints will not be a consideration for this design.

4. System interfaces

The SRMS is essentially a self-contained system for which there are few interfaces to external systems that require specification. Section 3.1 lists the requirements for power and attachment to the shuttle orbiter. Interfaces through which the operator interacts with the SRMS are found on the RMS control & display panel (Figure 2), and are largely specified in section 3.2 and section 3.3 of this document. All remaining user interface features of the RMS control & display panel to be used in the SRMS are specified in the requirements that follow.

R27: The RMS control & display panel shall incorporate an RMA Joint Status display area in which shall be displayed current angle, seek angle, velocity, and fault status for each of the six RMA joints.

R28: A master Fault indicator shall be incorporated on the RMS control & display panel that shall be illuminated when any SRMS subsystem reports a fault – including the RMA joint motor controllers.